EXPERIMENTAL DEMONSTRATION/ANALYSIS OF FIBER-BUNDLE-BASED RECEIVER PERFORMANCE

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Abstract

In order to track, acquire and maintain a free-space optical link between mobile platforms experiencing misalignment due to movement and atmospheric turbulence requires a different approach than traditional free-space optical transceivers. Recently, a fiber-bundle approach for beam steering at the transmitter was proposed and investigated that allowed tracking ot the receiver without the use of mechanical devices. A complimentary receiver using a collection of fibers behind an array of high power, small diameter lenses was found to allow lateral misalignments of up to 3 cm for a 1.2 cm array and up to 45 degrees of angular misalignment between the transmitter and receiver optical axes. This paper investigates methods for optimizing the receiver design, particularly in terms of maximizing throughput of the optical power to the electronic receiver. Theoretical and experimental analyses are used to examine two significant issues and suggest solutions. Maintaining alignment accuracy between the lens array and the collecting fibers is addressed by using a collimator array, thereby fixing each fiber to one lens, or specially constructed fiber array structures in a dedicated housing. A collimator array is preferable for ease of construction but presents trade-offs with respect to power collected and misalignment tolerance. Losses incurred when combining the signals from the many fiber elements is addressed using couplers, optical combining systems, and electronic summing. The advantages and difficulties of the methods are compared with regard to practical implementation.

Introduction

Free-space optical (FSO) communication can provide high-bandwidth optical connectivity in the “last mile” of data networks, especially when wired solutions are impractical or cost prohibitive. FSO is being seriously investigated as a means for establishing high-bandwidth links for other applications, including inter-satellite communication, airborne Internet, and battlefield communication [1-4]. Several of these applications require mobile FSO nodes that must be able to acquire and track other FSO nodes, which may also be mobile, over a variety of transmission distances. While the high bandwidth available with FSO makes it an attractive option for such applications, there are significant challenges that must be overcome in order to make a functional mobile FSO network a reality.

A significant challenge for mobile FSO links is addressing the need for highly accurate alignment of the transmitter and receiver to establish a viable connection, particularly when a fiber optic interface is used in place of a phototransistor. Traditional methods used for collecting the incoming light and coupling it to a fiber, such as those used in commercial building-to-building systems, make the link highly sensitive to alignment errors. For fixed nodes, sources of alignment error primarily involve movement of the platform (such as building sway) and atmospheric turbulence [2,5,6]. For nodes mounted on stable platforms, a number of practical solutions exist, including sophisticated control algorithms, quadrant detectors, fast-steering mirrors, and multiple beam transceivers. For mobile FSO systems, the number of potential sources of alignment error increases significantly [4–6] In addition to platform motion and turbulence effects, there are errors in the GPS data typically used to locate a target node, the gimbals, motors, and similar devices used to point the optical beam toward the target, and errors in the systems controlling the beam parameters [7]. The combination of all of these error sources effectively create misalignment, causing the transmitted beam to intercept the receiving lens at an angle to the optical axis and away from the central

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portion of the lens. Increased beam spreading and scintillation alters the power budget of the link and impacts design choices when using divergence to mitigate beam deflection effects.

FSO systems are susceptible to both translational and angular misalignment. The field of view of most commercial systems is typically a few tens of milliradians at most, and a few millimeters of misalignment between the optical axes of the transmitter and receiver result in a loss of signal. As the angular or translational error increases the focal spot of the receiving lens "walks off" the core of the receiving fiber. Only a fraction of the collected light intersects with the fiber core, rapidly decreasing the power collected by the fiber and thus the power presented to the eventual electronic detector. The random nature of turbulence causes the focal spot of a lens to take a random walk in the focal plane [5], [6], effectively modulating the signal-to-noise ratio of the link in a way that can cause periods of disconnection. Methods for mitigating the effects of the random walk, or conversely improving the angular and translational misalignment tolerance of the receiver, would improve the overall performance and reliability of the FSO link.

Recently, we have explored the feasibility of using a bundle of large-core optical fibers behind the lens of the receiver to increase the receiver's tolerance to both types of misalignment [8–10]. Theoretical and experimental analysis demonstrated that the fiber optic bundle did increase the misalignment tolerance, and that the improvement depended strongly on the size of the bundle used and the power of the collecting lens. A larger bundle, whether due to a large number of fibers or a smaller number of larger-cored fibers, particularly improved the range of translational misalignment that could be tolerated. Angular misalignment tolerance was more profoundly influenced by the focal length of the lens, with a shorter focal length (higher power) lens providing the most benefit. The solutions proposed were tempered by such practical considerations as the potentially large number of fibers needed and that powerful lenses tend to be small in size and therefore limit the critical power collecting capabilities of the receiver's optical system. An alternate solution was proposed to improve the design by using an array of lenses at the receiver, rather than a single lens, coupled to an array of large-core fibers in an effort to maximize both misalignment tolerance and optical power collected. Preliminary studies evaluated key parameters that provided the maximum allowable lateral, allowable angular misalignment, and collected power for both collimated and divergent beams. These initial studies found that the lens array provides superior performance over a single lens combined with a fiber bundle [10].

In this paper, we investigate further the lens array approach and evaluate its effectiveness in improving misalignment tolerance and hence maximizing up time of the link. The approach uses either a single fiber or a small bundle of fibers behind each lens in an array of small, short focal length lenses, with the outputs of the fibers summed for conversion of the signal into the electrical domain. The approach is evaluated on the key parameters of total collected power, maximum allowed translational misalignment and maximum allowed angular misalignment for several different choices of the lens characteristics and the diameter of the collecting fiber. A theoretical analysis of the system is presented to address the key parameters.

Overview of the Receiver System

The basic concept for the receiver system under study is depicted in Figure 1. A signal from a distant transmitter is incident on the receiver's optical system. If the transceivers are misaligned, the signal may come in at an angle to the receiver's optical axis, parallel to the axis but displaced from the receiver's optical axis, or both. In addition, the scintillation causes redistribution of the mean intensity of the beam, so that the peak intensity point(s) may no longer be near the center of the effective beam. To address these issues, the optical system at the receiver is divided into multiple subsystems in parallel with each other and having the same basic design. Each system has the ability to capture rays entering at a wider range of incident angles than traditional FSO receivers, and the use of systems in parallel improves the maximum displacement of the incident ray that can be tolerated. Parallel collection also makes it more likely that the peak intensity point(s) will fall on a part of the receiver where a large fraction of the power can be collected and directed toward the electronic detector. The individual signals are then combined to produce a composite signal for detection and further processing. The effectiveness of the parallel optical systems is the main focus of this work.

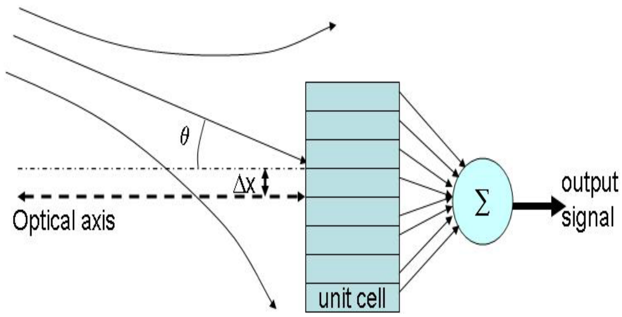


Figure 1. Overview of the Receiver System

One approach for implementing a multiple-lens solution that addresses practical implementation issues is shown in Figure 2. The first approach, shown in Figure 2(a), is to use relatively large lenses that each couple to a small bundle of large-core optical fiber.

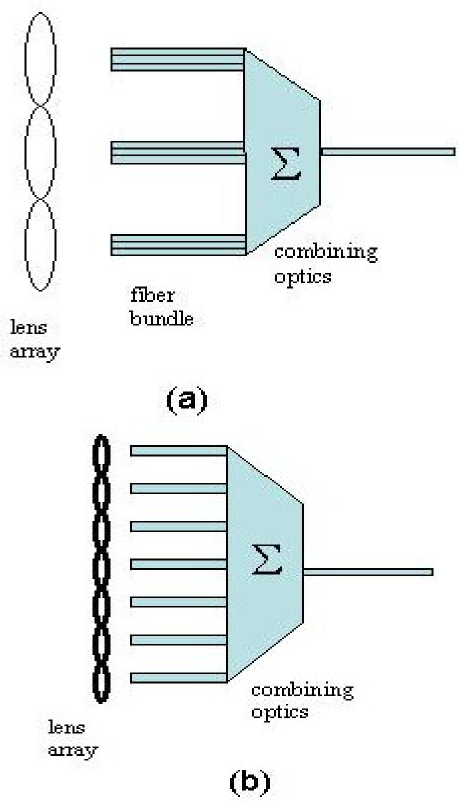


Figure 2. Two Receiver Options

The bundle is expected to be limited in size to a combination of seven fibers in a hexagonal arrangement to reduce the amount of fiber required. Each of the fibers surrounding the central fiber is positioned to capture light when the focal point wanders due to misalignment. The second approach uses what we refer to as the "bug's eye" approach, where a multitude of small, powerful lenses form a large lens array, and each lens in the array is coupled to a single large-core fiber. The small size of each lens limits how far the focal spot moves at the fiber plane due to translational misalignment, and thus only one fiber is required. The higher power (shorter focal length) of each lens reduces how far the focal spot moves at the fiber plane due to angular misalignment, and therefore a fiber with a smaller-sized core may possibly be used. An advantage of using a smaller-core fiber is its potential compatibility with commonly available multi-mode fiber devices and systems, which would increase the practicality of the design.

Collimator Approach

Using pre-constructed collimators to act as the collecting cells for the receiver is an enticing approach to the receiver design. This approach effectively implements the receiver option shown in Figure 2(b). For the collimator, the lens and the collecting fiber are aligned with high precision and this alignment is rigidly fixed by the housing package. This makes the individual cells and the overall array of collimators much less susceptible to manufacturing errors and mechanical vibration in the environment, especially in comparison to maintaining alignment between a lens array and a fiber array. Another likely advantage of using collimators is that little additional design of housings or other fixtures would be required to implement the approach.

The collimator approach was evaluated in the laboratory on the basis of collected power and tolerance of translational and angular misalignments. A bundle of seven collimators was constructed from commercially-available components. The collimators were designed for operation at 1310 nm wavelength and coupled to a standard multi-mode graded-index fiber with 62.5 μm core diameter. The collimator bundle was aligned with the transmitter so that initially the optical axis of the bundle and that of the transmitter were parallel, and the center of the transmitted beam was incident on the center of the bundle (the center of the central collimator). The receiver was placed just 2 meters from the transmitting aperture to minimize atmospheric propagation effects (turbulence, scattering). The output fibers were butt-coupled directly to a large-area infrared detector for measuring the total power collected by the array. For the basic experiment, the transmitter was unmodulated to simplify measurement and analysis, and the smallest beam diameter used extended just beyond the outer diameter of the collimator housing.

While the construction of the collimator array was simple as expected, the performance of the array with respect to misalignment tolerance was poor, especially for smaller beam sizes. The best allowable translational misalignment r_{max} achieved was 5 mm. The largest angular misalignment for which power was collected was only 2°, and the power collected at this angle was a mere 5 nW, compared to the 100 μW emitted by the transmitting antenna. This performance does not compare favorably with prior experimental studies performed on two lens "arrays" or the capabilities predicted by theoretical analysis presented previously [9]and later in this paper.

There are a couple of explanations as to why the performance of the commercial devices was poor for the application under investigation. Firstly, the vast majority of commercial collimators are designed with an entrance pupil that block light from striking the edges of the collecting lens. This entrance pupil not only limits the amount of light the collimator can collect, but also widens the area of the transition zone between adjacent collecting cells. Thus, for large-area beams that may cover more than one collecting cell or smaller-area beams moving from one cell to the next, the ability of the receiver to combine light from multiple cells is compromised by this transition region where no light is collected. Note that the transition zone would exist even in the absence of the entrance pupil, as the packing of the individual lenses would not fill the collecting area completely. Secondly, the collimators are most likely optimized for an input very nearly parallel to the optical axis – an angular misalignment of essentially zero.

Lens-Fiber Array Approach

The alternate approach is to design an array of lenses, coupled to a corresponding array of optical fibers, to maximize the misalignment tolerance of the receiver while attempting to minimize losses in optical throughput. The resulting design can be used to either (1) design a molded lens array and fiber array for mounting in a specially designed housing or (2) design a collimator-like device to use for each of the receiver cells shown in Figure 1. In an attempt to rapidly discern the key parameters for such an approach and guidelines on choosing those parameters, an approximate theory was developed and used as the basis of a simulation analysis.

Theoretical Formulism

To perform a basic analysis of the performance for the lens-fiber array approach, a simplified theoretical analysis is formulated based on the framework shown in Figure 3. An incoming beam with waist w_L enters the receiving lens at a lateral displacement r_{in}. An angular misalignment can be accommodated but is not indicated in Figure 3. The beam is directed towards a fiber located one focal length f_R from the lens. However, the ray is deflected a distance r_Δ off the optical axis of the fiber by the lens. The link can only be maintained if sufficient light is coupled to the fiber, and the amount of coupled light is determined by r_Δ, which is a function of r_{in} and f_R, the radius of the fiber core, and the power distribution of the incoming beam as determined by w_L. The maximum value of r_{in} allowed represents a measure of the maximum transverse misalignment the receiver design can tolerate.

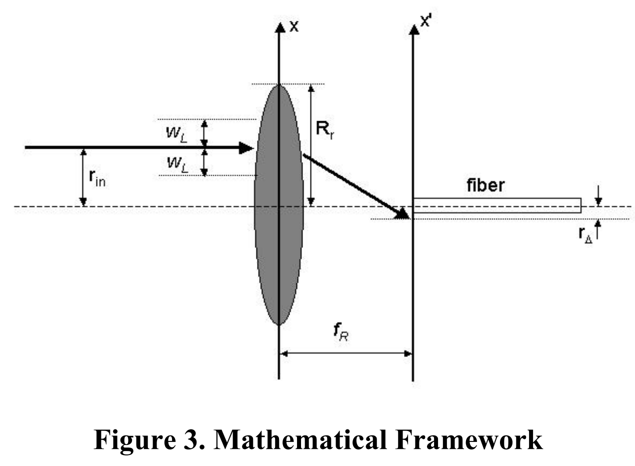


Figure 3. Mathematical Framework

To determine the relationship between r_{in} and r_Δ, we use transfer matrix theory using a lens of thickness d. Assuming a refractive index of 1.5 for the glass of the lens, r_Δ is given by

$$r_\Delta = r_{in}\left(1+\frac{d}{3R}-\frac{f_R d}{6R^2}\right)+\theta_{in}\left(f+\frac{2d}{3}-\frac{f_R d}{3R}\right),$$

where R is the radius of curvature of the lens surface and θ_{in} is the angular misalignment.

To come up with an approximate expression for the optical field at the fiber plane, we approximate the input Gaussian beam as a plane wave of limited spatial extent. The plane wave has constant amplitude A and extends a distance equal to w_L on either side of the central ray. Therefore the input field to the lens, E_{in}, is given by

$$E_{in} = \begin{cases} A & -w_L + r_{in} \le x \le w_L + r_{in} \\ 0 & else \end{cases}; \quad A = 0.5E_o\sqrt{\pi}$$

where the value of A is chosen to make the energy contained in both waves equal along the x direction. Using a communications theory approach [9-10] the electric field distribution in the x' direction at the fiber plane is

$$E_f(x') = \int_{-\infty}^{\infty} \frac{i}{\lambda f_R} E_{in} e^{ikn_l d} e^{-ikx^2/2f_R} e^{ikf_R} e^{ik(x'-x)^2/2f_R} dx.$$

Pulling out all of the terms that are not a function of x and grouping together in a constant C, we get the one-dimensional Fourier transform of E_{in} given by

$$E_f(p) = \Im[E_{in}] = C\int_{-\infty}^{\infty} E_{in} e^{-ipx} dx; \quad p = kx'/f_R$$

The result of this equation depends on whether the incident beam falls entirely on the lens or if some part is outside the lens area. Also, since a perfect lens with no aberrations is assumed, the shift r_Δ must be added into the result. The resultant solution for E_f is

$$E_f = \begin{cases} CA\cdot 2w_L \cdot sinc(w_L k(x'-r_\Delta)/f_R) \\ \quad \cdot\exp(-i2\pi r_{in} k(x'-r_\Delta)/f_R) & |r_{in}+w_L| < R_r \\ CA\cdot 2w_{beam}\cdot sinc(w_{beam} k(x'-r_\Delta)/2f_R) \\ \quad \cdot\exp(-i2\pi r_{eff} k(x'-r_\Delta)/f_R) & |r_{in}+w_L| < R_r \end{cases}$$

where w_{beam} is the width of that part of the beam intercepted by the lens and r_{eff} is the effective center of the intercepted beam, which are given by

$$w_{beam} = \begin{cases} R_r + w_L - r_{in} & r_{in}+w_L > R_r \\ r_{in} + w_L + R_r & r_{in}-w_L < -R_r \\ R_r & r_{in}+w_L > R_r \ \& \ r_{in}-w_L < -R_r \end{cases}$$

$$r_{eff} = \begin{cases} 0.5(R - w_L + r_{in}) & r_{in}+w_L > R_r \\ 0.5(-R + w_L + r_{in}) & r_{in}-w_L < -R_r \end{cases}$$

In order to determine the effective coupling of E_f to the fiber, an overlap integral is used, given generally by [11]

$$O = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} |E_{fiber}|^2 |E_{fund}|^2}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} |E_{fiber}|^2 \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} |E_{fund}|^2}.$$

where E_{fund} is the electric field distribution of the fundamental mode of the collecting fiber, and is closely approximated by a Gaussian distribution of

$$E_{fund} = B\exp(-x'^2/w_f^2)\exp(i\beta z); \quad w_f \ge r_{core}$$

where r_{core} is the core radius of the fiber. To find a closed-form solution we approximate the *sinc* function by a Gaussian distribution closely fitted to the shape of the central feature of the *sinc* distribution. Upon doing so, O is

$$O = \left[AB\,|\,C\,|\,(w_{eff})\right]^2\sqrt{\pi/a}\,\exp((b^2-4ac)/(4a)),$$

$$a = \frac{2}{w_f^2} + \frac{w_{eff}^2 k^2}{2f_R^2}; \quad b = \frac{-w_{eff}^2 k^2 r_\Delta}{f_R^2}; \quad c = \frac{w_{eff}^2 k^2 r_\Delta^2}{2f_R^2}$$

where w_{eff} is either $w_{brsm}/2$ or w_L depending on which case exists. We choose to normalize O by dividing the equation by the constants in front of the exponential.

We now set a lower limit O_{min} on the value of O that represents the lowest power coupling into the fiber for which a link can be established at the desired BER. Thus we set and solve for the value of r_{in} that meets this condition.

$$(w_{eff}^2 \sqrt{\pi / a}) \exp((b^2 - 4ac)/(4a) = O_{\min}$$

This value of r_{in} is now r_{max}, the maximum allowable displacement between the transmitter and receiver. The value of r_{max} is recalculated as the incidence angle θ_{in} is varied to determine the receiver's angular range of operation.

Simulation Analysis

Simulation Parameters

Several lenses of different size and focal length were used to determine the effects of these parameters on the receiver performance. A sampling of biconvex lenses was selected from Newport Corporation due to availability of detailed specification information. The lenses ranged in diameter from 6.35 mm to 25.4 mm and in focal length from 12.7mm to 25.4mm. When comparing lenses of different size, the number of lenses was chosen to roughly equalize the collecting area for each case, an example of which is shown in Figure 4.

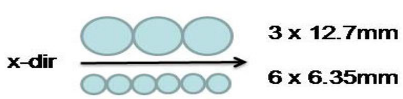


Figure 4. Lens Configurations

Several different fiber types and arrangements were also used, to determine the effects of these design choices on the receiver performance. The fiber diameters investigated were 800, 400, and 62.5 μm, with the last one reflective of the core size for standard multi-mode fiber used in optical communication systems. Either a single fiber or a bundle of 7 fibers was used to collect the light from each lens of the array. The fibers in all cases were positioned at the nominal focal length of the lens.

The results of any simulation depended strongly on the choice of the incident beam waist w_L. For initial evaluations, the value of w_L was varied over a wide range and the best possible performance point – in terms of r_{max} – was chosen to represent the best possible misalignment tolerance achievable with the design under test. The corresponding value of w_L was not necessarily constant for every value of incidence angle θ_{in} for this procedure. Continuing evaluations are investigating the choice of w_L that coaxes the best overall performance out of a given design.

Simulation Results

Figure 5 shows typical outputs obtained from the simulation. The receiver lens used to obtain these particular results had a focal length f_R = 12.7 mm, thickness d = 6.680 mm, diameter of 12.7 mm, and radius of curvature of 11.868 mm. Three lenses distributed along the x-direction were used, with a single 400 μm core diameter fiber placed behind each lens. Results are shown for the maximum allowable misalignment r_{max} for four different cases of incident angle θ_{in}.

The behavior observed in Figure 5 is common to all of the cases investigated as part of the study. When no angular misalignment is present (θ_{in} = 0), r_{max} is highest generally in an area where a long transmitter focal length and a source fiber position close to the focal point create a relatively large, very-nearly collimated beam. A decrease in r_{max} occurs as either the divergence increases or the beam diameter decreases, which is a reasonable conclusion. As the angular misalignment increases ($\theta_{in} > 0$), two patterns emerge. First, the maximum achievable value of allowed misalignment r_{max} increases. This behavior is most likely explained by noting that the central high-intensity portion of the beam is skewed lengthwise along the x-direction due to the beam angle, allowing for available beam power along a larger range of translational misalignments r_{in}. Second, the range of conditions for which a viable connection is made begins to narrow. The value of r_{max} decreases and eventually becomes zero in the upper right corner of the graph first, corresponding to the same large, low-divergence cases where r_{max} was maximum when $\theta_{in} = 0$. Cases that produce a larger divergence become preferred, and provide the only practical choice for maintaining a connection at higher θ_{in} values. For the example presented here, the link designer would need to choose a moderate focal length lens (say 0.7 meters) and position the fiber tip at distance equal to 0.999*0.7 meters to allow the link to function with angular misalignments up to at least 12°.

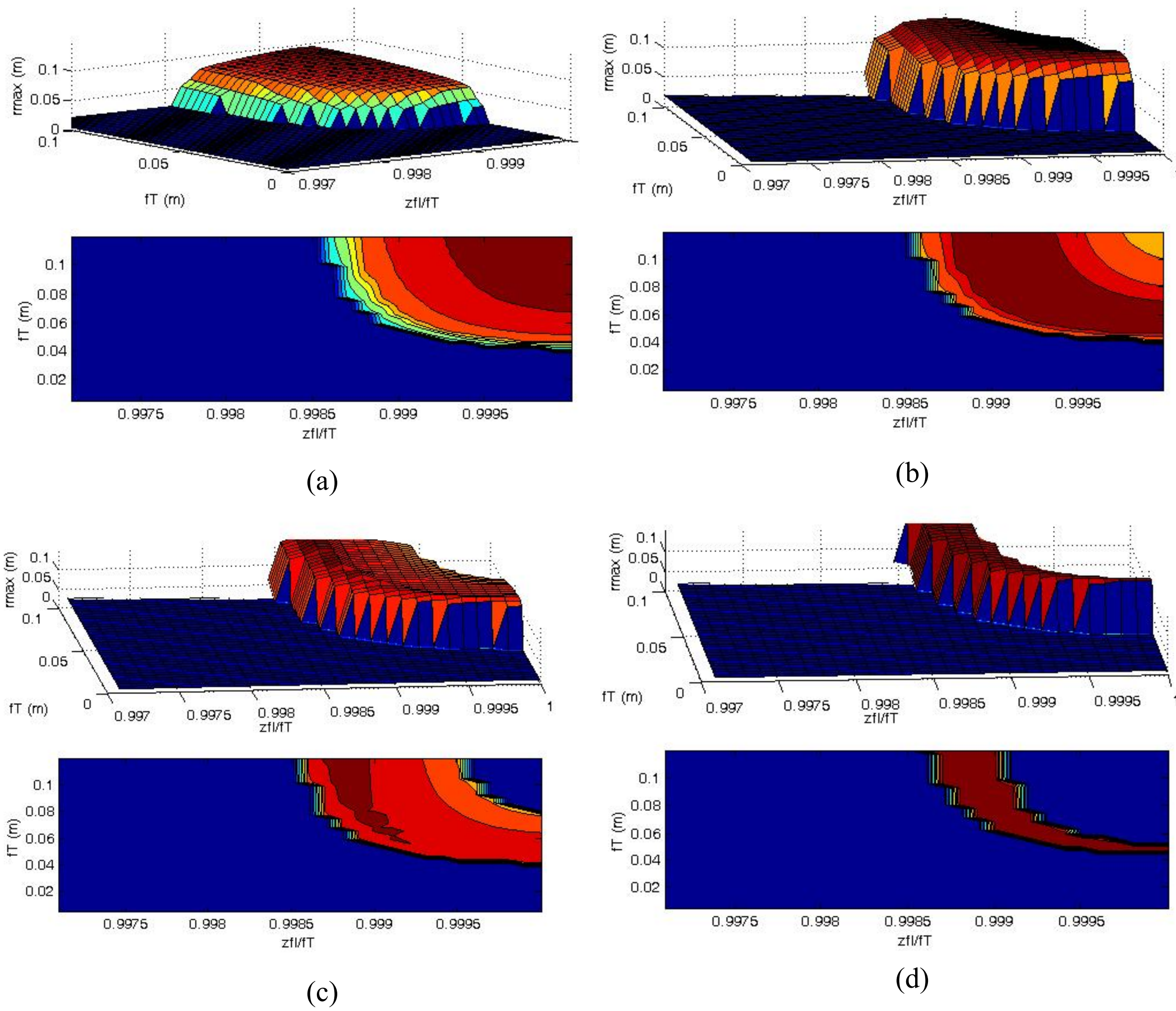
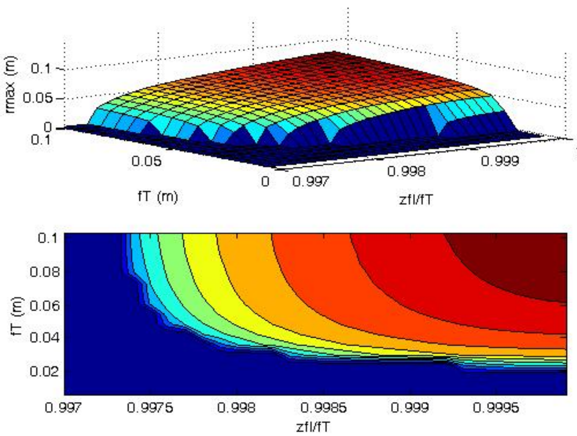


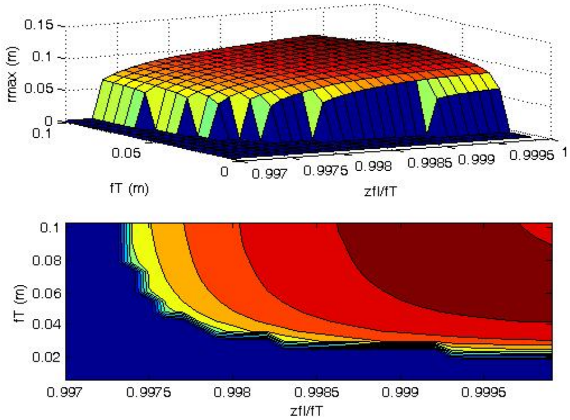
Figure 5. 12.7mm (a) 0° (b) 5° (c) 10° (d) 12°

The simulation was repeated for a lens of the same focal length (12.7 mm) but only 6.35 mm in diameter. Other parameters of the lens were $d = 3.820$ mm and a radius of curvature of 12.440 mm. To balance the collecting areas between the two simulation cases, six of the smaller lenses were used. Some examples of the results are shown in Figure 6.

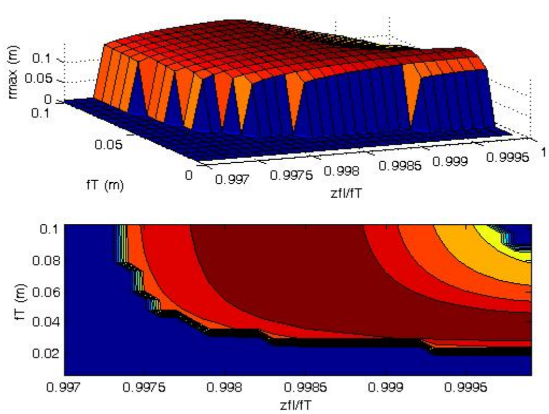
There are several notable differences when using the smaller lens over the larger lens. First, the value of r_{max} is lower at the smaller angles. Much of this is attributable to the fact that, while the total lens area available is approximately the same, the lens area intersected by the beam in each case is actually less, since there are more gaps between the lenses. Even extending the calculation to the entire two-dimensional receiver area would expose these gaps, and this is unavoidable as long as the lenses are assumed discrete in nature. A practical lens array would be designed to eliminate these gaps, allowing nearly equivalent power collection in the two cases, which would likely result in more equivalent achievable values of r_{max}. Second, the range of divergence angles allowed for each choice of lens focal length is much larger for the smaller lens. For example, z_{fl}/f_T can range from 0.9975 to 1.0 for the 6.35 mm diameter lens with f_T = 10 cm, while the larger lens with the same focal length has a usable z_{fl}/f_T range of 0.9986 to 1.0. From a design perspective, this makes a receiver that uses the smaller lens design more tolerant to inaccuracies in the generation of the transmitted beam parameters. Third, the smaller lens exhibits a much higher angular misalignment tolerance, as there is still a fairly large usable range of conditions for establishing the connection at an angular misalignment of 20 degrees.



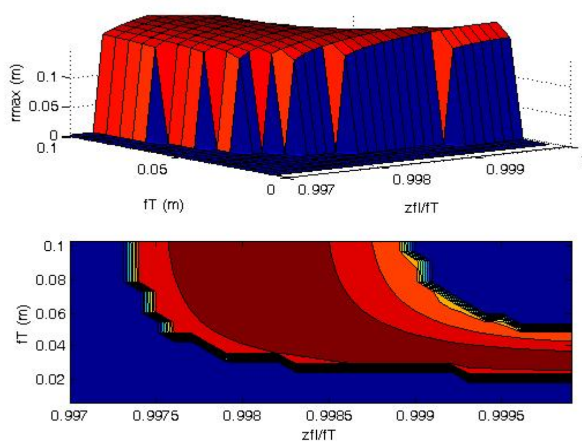
(a)



(b)



(c)



(d)

Figure 6. 6.35 mm lens (a) 0° (b) 5° (c) 15° (d) 20°

The one aspect of the receiver's performance that is not explicitly determined from Figures 5 and 6 is the relative power collected by the optical fibers. The simulation does record the collected power, and the results for the two example cases above are shown in Figure 7. The collected powers presented are the maximum possible over all choices of transmitting lens and divergence angle. For large collecting fibers, the smaller lenses, coded "13" in the legend of the graph, collected a similar amount of power at small angular misalignment as the larger lenses, coded "22" in the graph. The smaller lens demonstrates the ability to direct more power into the fiber at larger input angles, which leads to the better angular performance in

Figure 6. This ability is demonstrated for all of the collecting fiber types explored. However, as the diameter of the collecting fiber decreased, the larger lens outperformed the smaller lens in terms of the amount of power delivered to the fiber at small angles, with the discrepancy in performance growing larger as the fiber became smaller. The smallest fiber used was a standard 62.5 μm core diameter multi-mode fiber. For this fiber, there is a distinct trade-off between angular range and collected power when choosing which of the lenses to include in the receiver optics.

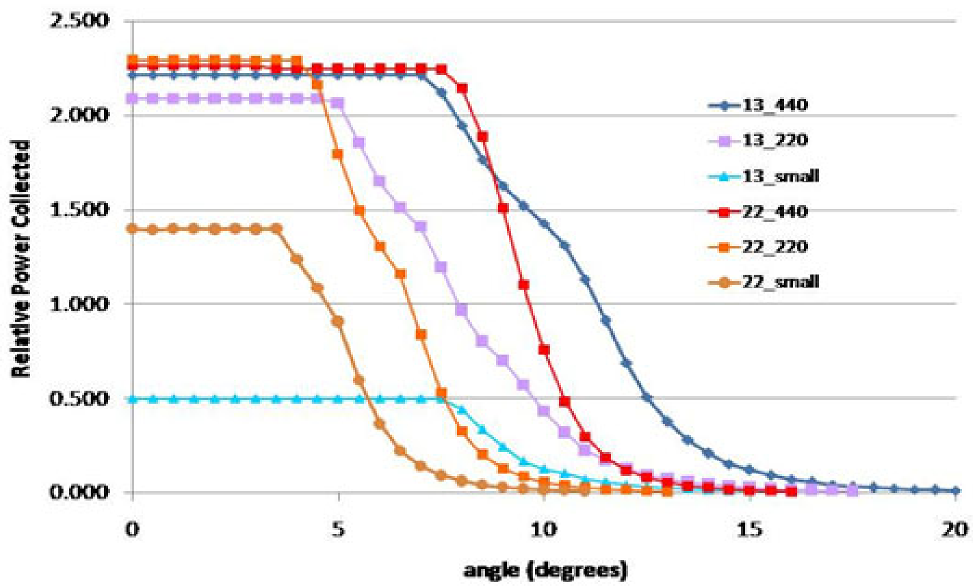


Figure 7. Relative Output Power vs. θ_{in}

The same evaluation was carried out on another 6.35 mm lens with a smaller focal length (6.4 mm) than the one studied in Figures 6 and 7. A shorter focal length has potential to more readily bend errant rays back towards the optical axis, and hence back into the optical fiber. The negative aspect of the shorter focal length is a larger incidence angle on the fiber and larger aberration effects, especially when the incoming rays are closely parallel to the optical axis. In this case the acceptance angle of the fiber may be exceeded, in which case the light will not be collected even if it impinges on the fiber core. A comparison between the 12.7 mm lens and 6.4 mm lens was performed to determine whether the negative or positive potential aspects of using the shorter focal length prevailed.

The results of this evaluation are shown in Figure 8. The data clearly indicated that the use of the shorter focal length lens is not warranted. Except when using the smallest collecting fiber, the 12.7 mm lens couples significantly more optical power to the fiber than the 6.4 mm lens does. The 6.4 mm lens shows greater tolerance of angular misalignment for the largest fiber core, where its superior light bending power can be most readily exploited. However, the 12.7 mm lens performs equally well or better than its shorter focal length counterpart as the diameter of the fiber decreases. Note that earlier work has shown that increasing the focal length and or size of the lens can also degrade performance for optical coupling [9-10]. Thus there appears to be an optimum choice of focal length and size for the receiver lens that can be discerned readily through simulation studies.

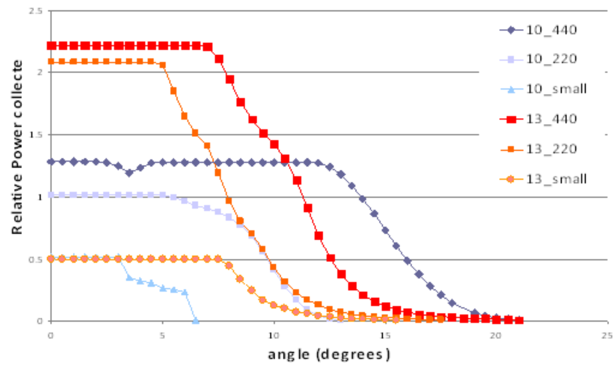


Figure 8. Comparison Between Two Lenses

Signal Combination Approaches

The challenge posed by using the cellular design for the receiver depicted in Figure 1is that the signals collected by each cell must at some point be recombined to create a single signal for use by the receiver electronics. The options for performing this recombination are limited by a conscious choice to have the optical signal collected by a fiber first, rather than coupling the lens array directly to an array of phototransistors. This choice preserves to some degree some of the advantages of using fiber in the receiver, such as a limited ability to create interference using an independent transmitter, which is a security concern.

Three possible approaches provide potential solutions to the recombination problem. These approaches are to (1) use a coupler or (2) other optical combining system prior to presenting the light to the phototransistor, and (3) to couple each fiber to a phototransistor and then perform the recombination electronically. Each of these methods has advantages and disadvantages in the current application.

Optical Coupler Recombination

Several attempts were made in the laboratory to employ a commercial optical splitter/combiner to recombine the signals from multiple fibers into a single fiber. Splitters ranging from 1x2 to 1x8 from different manufacturers were evaluated. The attraction of this approach is an existing, well-engineered part that can be quickly integrated with the rest of the receiver's optical system. However, in all of the experiments, regardless of the splitter type or manufacturer, large losses were observed when trying to use the device as a combiner. The loss increased as the number of fibers to be combined increased, which is a significant disadvantage of using this approach. Another disadvantage is that commercial systems are usually limited to using single mode fiber or graded-index multimode fiber, and thus are not readily adaptable to other fiber sizes that may otherwise improve the receiver performance for certain applications.

Alternative Optical Recombination

Several methods exist for combining disparate optical signals using bulk optical components rather than waveguides. One limiting factor in the current application is that a large number of signals must be combined and focused onto the small collecting area of a high-speed phototransistor. An added concern is the phase shifts that may occur between the individual outputs, which effectively broaden the pulse and allow for destructive interference at the summing plane. After reviewing a number of possibilities, the use of an aspheric condensing lens appears to be the most promising approach. By using an aspheric lens of the appropriate focal length, a broad image – here the output planes of bundled fibers – can be readily condensed onto a small area at the focal plane of the lens where it is collected by a phototransistor. The advantage of this method over the optical coupling method is the much higher efficiency of transferring optical power from the collecting fibers to the receiving electronics. The advantage of this method over the electronic summation approach is that it only requires one set of receiver electronics and coupling optics. The question regarding phase delays between outputs still needs to be addressed, and experiments are in process to determine how this impacts the signal-to-noise ratio and bit-error rate of the signal.

Electronic Summation

The final approach considered is to combine the signals in the electrical domain instead of the optical domain. In this approach, each fiber in the receiving array is coupled to an individual phototransistor. The electronic signals generated by the phototransistors are then summed together prior to processing by the remaining electronics and extraction of the transmitted data. A variation of this approach has been investigated where a lens array was coupled directly to an array of phototransistors. An attractive property of this approach is that all of the optical paths (the fibers, essentially) are easily made to have the same length, so that the main source of any propagation delays would occur only at the electronic level. Careful design of the electronic summing circuitry may minimize these propagation delays and facilitate high-speed communication, despite the need for the phototransistors to be spaced apart (125 μm centers for standard multi-mode fiber) to accommodate for the size of the fibers used. This approach is considered a strong alternative to optical combination using the aspheric lens, with the main concern being the need to implement a multitude of detection circuits and the associated expense.

Summary

In this work, we have investigated further the lens array approach to improving both translational and angular misalignment tolerance at the receiver end of the link and hence maximizing the up time of the link. Several key parameters, including the collected power, maximum allowed translational misalignment and maximum allowed angular misalignment, were used to evaluate the performance of a collimator-based approach and a coupled lens-fiber array approach. While the collimator approach provided some advantages, the performance was overall poorer than that potentially achieved with the lens-fiber array approach. A theoretical analysis of the latter approach showed that a smaller lens of moderate focal length has promise for achieving an optimum combination of the key performance parameters for larger-cored collecting fibers. As the core are of the collecting fiber decreases, a somewhat larger lens is required to couple sufficient optical power into the fiber, though a moderate focal length (not to small, not to large) is still a practical design choice. This information can be used to design an appropriate lens array or guide the design of a collimator-like system with a rigid housing that facilitates simpler construction of the receiver.

Several approaches were considered for combining the output signals from the receiving fiber optic array. The preferred approach for optical summation of the signals is the use of an aspheric condensing lens with a phototransistor placed at the focal plane. Electronic summation of the signals is a strong alternative to the optical summation approach. The ultimate choice depends on the ability to minimize phase delays between the multitude of signals and whether the system is practical to construct.

References

[1] Dodley, J.P., D.M. Britz, D.J. Bowen, C.W. Lundgren, 2001, "Free space optical technology and distribution architecture for broadband metro and local services," Proc. SPIE, vol. 4214, pp. 72-85.

[2] Amon, S., 2003, "Optimization of urban optical wireless communication systems," *IEEE Transactions on Wireless Communications*, vol. 2, pp. 626-629.

[3] Amon, S., S. Rotman, N.S. Kopeika, 1997, "Beam width and transmitter power adaptive to tracking system performance for free-space optical communication," Applied Optics, vol. 6, pp. 6095-6101.

[4] Ho, T.-H., S. Trisno, I. I. Smolyaninov, S. D. Milner, C. C. Davis, 2004, "Studies of pointing, acquisition, and tracking of agile optical wireless transceivers for free space optical communication networks," Proc. SPIE, vol. 5237, pp. 147-158.

[5] Andrews, L.C., R. L. Phillips, 2005, Laser Beam Propagation through Random Media, 2^{nd} ed., SPIE Press.

[6] Andrews, L.C., R. L. Phillips, R. J. Sasiela, R. Parenti, 2005, "Beam wander effects on the scintillation index of a focused beam," Proc. SPIE, vol. 5793, pp. 28-37.

[7] Harris, A., J. Sluss, Jr., H. Refai, P. G. LoPresti, 2005, “Comparison of active beam steering elements and analysis of platform vibrations for various long-range FSO links,” Proc. SPIE, vol. 5819, pp. 445-462.

[8] LoPresti, P. G., H. Refai, J. Sluss, Jr., I. Varela-Cuadrado, 2006, “Adaptive divergence and power for improving connectivity in free space optical mobile networks,” Applied Optics, vol. 45, no. 25, pp. 6591-6597.

[9] LoPresti, P. G., H. Refai, 2007, “Mitigating angular misalignment from atmospheric effects in FSO links,” Proc. SPIE, vol. 6551, p. 65510K.

[10] LoPresti, P. G., C. Kiister, S. Spaunhorst, H. Refai, 2008, “Maximizing receiver misalignment tolerance in a hybrid wireless system,” Proc. SPIE, vol. 6951, p. 69510N.

[11] Agrawal, G. P., 1989, Nonlinear Fiber Optics, Academic Press, San Diego, California, p. 174.

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